

Selective Internal Heat Distribution in Modified Trombe Wall

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Abstract. At present, the requirements for thermal insulation of the external walls in buildings are being increased. There is a need to reduce energy consumption for heating rooms during the winter season. This may be achieved by increasing the thermal resistance of the outer partitions, using solutions that utilize either recuperation or solar radiation. The most popular systems include either solar collectors, or heat pump links or ground exchangers. Trombe walls (TW) are a very promising passive heating system, which requires little or no effort to operate, and may be very convenient in different climate conditions. A typical TW consists of a masonry wall painted a dark, heat absorbing paint colour and faced with a single or double layer of glass. The principle of operation is based on the photothermal conversion of solar radiation. There are various modifications of TW. They may improve the energy efficiency in relation to the climate conditions in which they operate. The hybrid solutions are also known. The efficiency of walls is related to the use of proper materials. In TW, the compromise should be sought between the thermal resistance and the ability to distribute heat from the absorbed energy of solar radiation. The paper presents an overview of the most commonly used solutions and discusses its own concept dedicated to the climate conditions of Central Europe.

1. Introduction

A Trombe wall (TW) is a system dedicated to indirect solar heat gain. The typical Trombe wall consists of glazed walls and massive walls. Glazing is functioning as selective transparent insulation. It has the ability to transmit high-energy short-wave solar radiation, while simultaneously blocking outflow to the external environment the heat generated by photo-thermal conversion. The basic function of the wall is to store and distribute the absorbed sunlight. Therefore, the wall material should have a high heat capacity [1]. Construction materials such as concrete, stone and brick are commonly used, and the wall thickness is between 10 and 41 cm [2]. If the wall thickness its heat storage capacity grows. At the same time, fluctuations in the temperature of its internal surface caused by the absorption of solar radiation decreases.

One way to increase the heat capacity of a wall is to use the *Phase Changing Materials* (PCM) in its structure. The material phase transition is possible after exceeding the specified limit temperature, appropriate for each material. This phenomenon is accompanied by energy consumption, which is given back during the return to the starting material point. The phase transition energy is determined in relation to the unit of mass or unit volume. As far as paraffin and organic compounds are concerned, it is up to 250 kJ/dm³, and in case of salt hydrates it is not exceeding 400 kJ/dm³ [3,4]. The basic parameters characterizing materials of this type are as follows: phase conversion heat and phase transition temperature. PCM is limited by its operation at temperatures that allow for phase transition.



In the case of collector-accumulative walls, this temperature may exceed 70°C. PCM by storing the energy needed for phase change limits the increase in wall temperature and consequently the escape of radiant heat through the transparent cover. The stored heat along with the solidification of the material is transmitted with some delay to the wall, prolonging the effect of its heating. It also brings the benefit of limiting wall temperature fluctuations, improving comfort in the use of adjacent rooms. It is noted that the walls containing PCM require less space and are lighter in comparison to the massive walls of the same heat capacity [5]. This advantage can be especially important in the situation of very high cost of usable area. Based on the numerical analysis carried out by Bourdeau [6] and cited in [5], a 0.15 m thick concrete wall can be replaced by a wall made of PCM with a thickness of only 3.5 cm and the same thermal capacity. Khalifa and Abbas [7] studying the hydrated encapsulated salt, found that a 8-cm thick wall containing hydrated salt had a higher heat storage capacity than a 20 cm thick concrete wall. In addition, the PCM wall reduced the amplitude of the temperature fluctuation by 3°C. It also had the ability to give heat at night twice as long as the concrete wall [7]. In the examples of collector-accumulative walls (CAW) mentioned above, material solutions used in wall constructions are not universal in terms of their effect on optimal energy balance, irrespective of prevailing climatic conditions.

The selection of a TW transparent cover is a compromise between the ability to pass solar radiation to the glazing and its thermal insulation. The type of transparent cover depends on the climatic conditions. Koyunbaba and Yilmaz experimentally compared TW, using different types of glazing: single, double and integrated with a photovoltaic panel, in Izmir (Turkey) [8]. The research has shown that the largest energy savings were achieved with the single-glazed TW system. Kisilewicz [9] based on simulation calculations carried out using a one-dimensional model, stated that the use of CAW insulation in the construction of partition walls is insufficient for the use of PKA in Poland due to low outdoor air temperature and high irregularity of sunlight. In order to increase the thermal insulation of the wall in winter and to prevent overheating in summer analogous to the direct profit system, it is recommended to use mobile insulation. Glazing in non-ventilated walls is installed in close proximity to the absorber so as to reduce the heat losses associated with the convection between the absorber and the glazing. This distance should be taken according to Torcellini et al. [2] in the range of 2-5 cm, and according to Hordeski [10] between 3–6 cm. It is proposed to eliminate the gap and to place between the panes and the wall with a honeycomb structure [11] in order to limit the heat loss throughout the transparent cover.

2. Characteristics of the selected Trombe' walls

The distribution of heat in the simplest non-ventilated wall as in figure 1 is primarily due to conduction within the wall. Once the thermal wave has reached the inner surface, heat is transferred to the adjacent room as a result of radiation and convection. The duration of this phenomenon may be several dozen hours. It depends primarily on the amount of radiation absorbed, as well as the wall thickness and its physical parameters [12].

The fluctuation in temperature over time $T_m(t)$ in a one-dimensional problem, along the thickness of the wall made of a material with a conduction coefficient of heat λ_m , density ρ_m and specific heat c_{w_m} , is described by the differential equation of the transient conduction as:

$$\frac{\partial T_m}{\partial t} = \frac{\lambda_m}{\rho_m \cdot c_{w_m}} \cdot \frac{\partial^2 T_m}{\partial x^2} \quad (1)$$

In the air voids, the heat exchange takes place as radiation, which in particular in transparent casings, especially filled with gases, can have a much greater effect than convection. The case of the ventilated wall, as in figure 2 distinguishes the method of heat transfer. The rise in temperature of the absorber is accompanied by the heating of the air in front of it. By the convection of a free or forced stream of heated air transports heat directly to the adjacent room. The vacuum created during this time in the air

void from the absorber is compensated by the suction of the lower air hole from the adjacent room. Proper circulation is affected by the width of the air gap between the glazing and the absorber. The dimension should be chosen so that the resistance of the flowing air is reduced. According to Sparrow et al. [13] the width of the space between the glazing and the absorber should be greater than 4.7 cm. After the time needed to pass the thermal wave through the wall to the adjacent room, the remaining part of the stored heat is supplied.

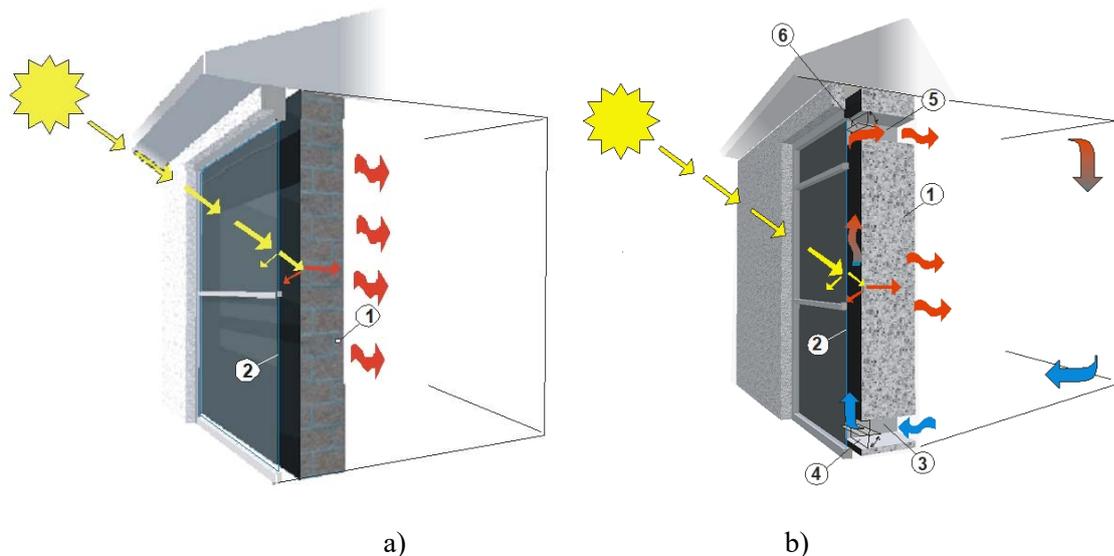


Figure 1. Schematic diagram of the Trombe' wall: *a)* non-ventilated, *b)* ventilated; 1 - wall, 2 - transparent cover, 3, 5 - ventilation holes, 4, 6 - throttles.

According to the findings of Balcomba and McFarland [14], cited by Saadatian et al. [15,16], the use of adjustable ventilation holes does not significantly affect PKA performance in mild climates. On the other hand, according to Bina et al. [17] the use of circular openings in a cooler climate can improve the efficiency and functionality of the solution. Thanks to the ability to absorb heat from the space along the absorber, the possibility of excessive increase of the absorber temperature is reduced, and consequently the heat loss through the glazing, proportional to the temperature. In massive walls with a thickness of over 35 cm, the use of closed flaps, throttles, special foils [18] and similar solutions can yield a 10-20% increase in productivity [19], as well as it may support cooling in the summer. The effect of heat exchange through circulation is closely related to the optimization of the opening and closing times of the circulation holes' flaps [20-21].

The information on the impact of using the Trombe ventilated wall in the building housing on the level of energy savings for heating are varied. Because the research was conducted under different climatic conditions, the difference in the level of savings was up to several tens of percent. Bojić et al. [22] using the ENERGY Plus software to climate analysis in Lyon (France), proved that the energy savings from the Trombe ventilated wall are equal to 20%. The same level of energy savings is also confirmed by the results of the measurements made at an existing facility in Zion National Park (Utah, USA) [17]. Moreover, the work of Nowzari et al. [23] shows the results of analyses carried out in the TRNSYS (Transient System Simulation) program of a 120 m² building equipped with a 15 m² TW in Cypriot climatic conditions and a reduction in heat demand of approximately 45%. At the same time, the Life Cycle Cost Analysis (LCC) showed that the construction of this type of wall is more economical than purchasing a 3kW gas boiler. Similar results of simulations performed under analogous climatic conditions have been reported by Kalogirou et al. [24]. The 25-cm wall mounted on the south side reduced the heat demand for heating the model building by about 47%. The study conducted by Dimassini [25] in the Tunisian climate showed that the efficiency of ventilated wall was

in the range of 31.7-45%. An analogous 30.2% efficiency of the collector-accumulation wall under the conditions typical for the period from November to March in Beijing, China is shown by Fang [26,27]. Jabar et al. [28], as a result of TRNSYS 'optimization of the TW ventilation wall area against the southern wall surface area to achieve maximum energy savings, estimated energy savings on the level of 37.55%. This value corresponded to a 37% share of TW in the southern wall surface.

In the solution operating under the name of the composite wall (Figure 2), the building element separating the glazing from the room is made in the composite technology. It is divided into layers, each of which has a separate function: absorption-insulating [29,30,31], absorption-storage and insulating [19,22]. In the collector-accumulative composite wall, in addition to the heat-storage wall, a wall made of materials with high thermal resistance is also used. Its task is to raise the thermal insulation of the entire wall. The wall in the lower and upper part is equipped with circulation channels that connect the space between the walls with the adjacent room, allowing the convection heat transfer to the building.

The insulating wall has considerable thermal resistance, so that the wall in winter, during the night and during the cloudy sky does not show any significant heat loss. In summer, the wall protects against the penetration of heat. An additional advantage of the composite wall is the ability to adjust the heating intensity by controlling the air flow in the circulation channel. TRNSYS simulation studies [18,19], have shown greater composite wall efficiency compared to the classic TW, operating in cool and moderate climate.

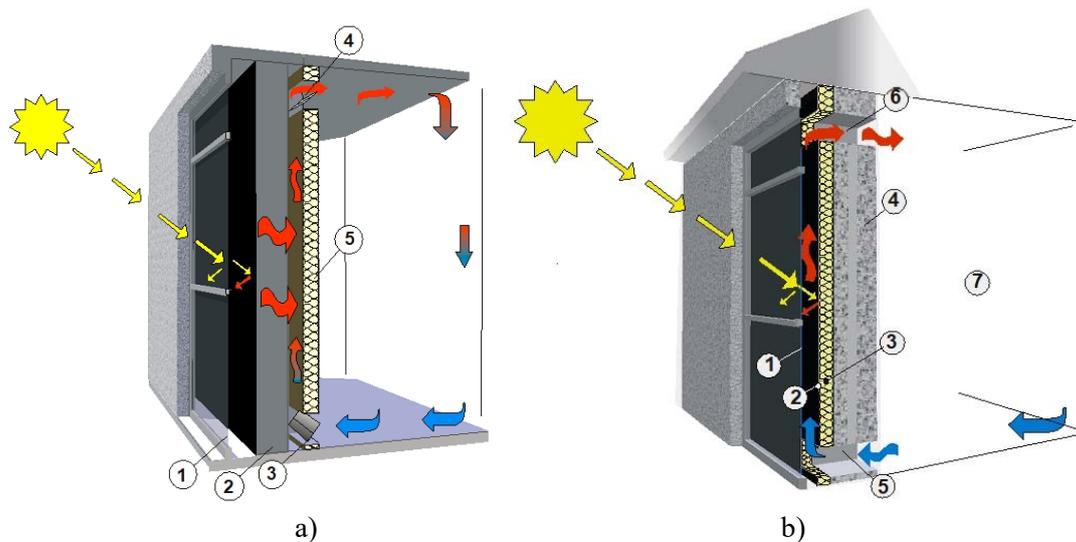


Figure 2 a) Composite wall: 1 - glazing, 2 - accumulating wall, 3, 4 - closed ventilation openings, 5 - insulation wall, b) modified wall composite: 1 - glazing, 2 - absorber sheet steel 3 - thermal insulation (10 cm), 4 - brick layer, 5, 6 - circulation channels, 7 - heated room

Certain fears may result in a temperature distribution in the cross-section of the wall, and especially on the surfaces limiting the air gap, between the accumulation wall and the insulating wall. The construction of the thermal insulation layer from the inside of the building makes the surface of the wall along the space in which the air circulates reach a temperature below the dew point with the characteristic humidity of the air in the utility room. According to simple calculations, already at outdoor air temperature of 0°C, condensation may occur at a water vapour pressure of 12.03 hPa corresponding to a relative air humidity of 50%. At a temperature of outdoor air equal to -10 °C, the risk of condensation already occurs at a humidity in the building at the level of 33%. The periodic moisture of the channel surface during long-term use carries the risk of developing microorganisms and their entry into the adjoining room with circulating air. Use of the air purification filters forces solutions based on mechanical circulation and increases the operational costs. Luo et al [31] discusses the variation of the composite wall. It uses a selective absorber made of sheet steel. Between the

absorber and the wall, a thermal insulation of 10-cm was placed (Figure 2.b). Numerical simulations of wall were carried out for the climatic data of Xining City, Qinghai Province, China. The difference in prototype performance was compared to the classical wall working under identical conditions. The efficiency of the solution is calculated as the ratio of the heat entering the room to the total solar radiation reaching the wall. As a result of the research, it was found that the efficiency of the prototype was 33.85%, which, according to the authors, was an increase of 56% in comparison to a typical TW working under the same conditions.

3. Study of a modified TW wall dedicated to the climatic conditions of Central Europe

The climatic conditions in Central Europe, due to the irregular and lower values of sunlight than in the south of Europe, are a contraindication to the choice of typical solutions with low thermal resistance. The implementation of typical ventilated or composite walls to weather conditions in Poland is associated with the risk of condensation inside the wall. This excludes the combination of air voids of the wall with the usable environment.

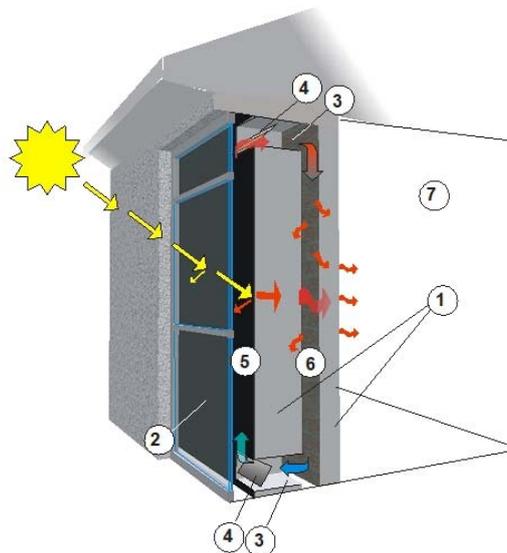


Figure 3. Slotted collector-accumulation wall (CAW): 1- wall consisting of two parts, 2 - manifold transparent cover, 3 - circulation channel, 4 - throttles, 5 - space between glazing and absorber (outer slot), 6 - inner slot, 7 - utility room

As a result of the above observations, it is proposed to construct the slotted collector-accumulation wall (Figure 3). It is an attempt to find a compromise between the satisfactory value of the wall's thermal resistance, while retaining its ability to generate heat from solar radiation. The total thermal resistance of the walls consists of thermal resistance of glazing, air voids and masonry itself. Construction wall based on the use of autoclaved aerated concrete, i.e. material that can significantly increase the thermal resistance of the barrier, may improve the heat transfer in the interior by using the internal air circulation. For this purpose, the core of the wall was divided into two parts. The gap between the absorber and the glazing (Figure 3) in the lower and upper part of the wall is connected by the channels. Thanks to this, the distribution of heat in the wall is possible due to the conduction and circulation of warm air between the voids before the absorber and the internal gap. The SPKA wall is structurally closest to the composite walls [18,19,31,32] but does not have a separate insulation layer and, as mentioned earlier, it does not allow direct air exchange with the adjacent room.

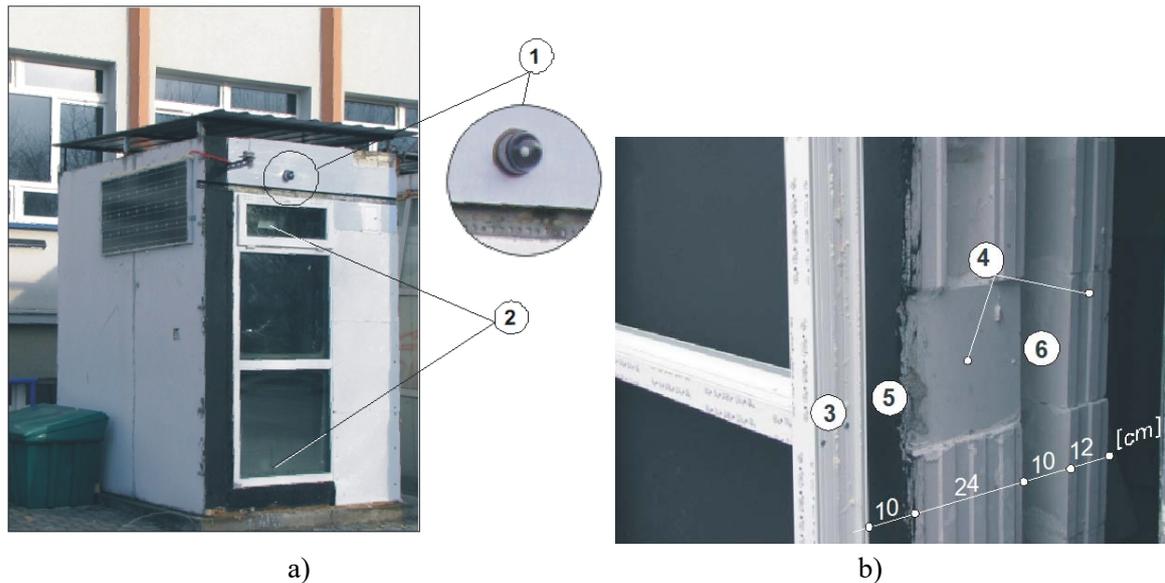


Figure 4. The research chamber: a) view, b) cross-section; 1- Almemo pyranometer, 2 - location of circulation openings; layout of wall layers: 3- PVC frame of transparent cover, 4 - wall, 5 - air gap between glazing and absorber, 6 - inner slot.

In order to determine the efficiency of solutions field tests in close to actual scale were performed. A prototype of the wall was placed in a special chamber with adjustable internal temperature (Figure 4). Two types of glass were used: double-glazed glass type with heat transfer coefficient $U_g = 0.6$ [W/m²K] with its ability to pass solar energy equal to $g = 0.59$ and single-glazed glass with coefficient $U_g = 1.2$ [W/m²K] with the ability to transmit sunlight energy equal to $g = 0.64$. As wall material, concrete (C) with density $\rho=2,200$ kg/m³, and autoclaved aerated concrete (AAC) with density $\rho=750$ kg/m³, as well as Calcium Silicate bricks (CS) with density $\rho=1,600$ kg/m³ is checked. The division of the wall into outer part 24 cm and inner 12 cm was assumed. The thicker outer part of the wall, due to its higher heat capacity, was responsible for storing and transferring heat from the absorbed sunlight. The inner part of the wall core was responsible for exchanging heat between the inner channel and the adjacent room, preventing direct air exchange between the interior of the wall and the adjacent room. Adopted thicknesses of 24 and 12 cm are typical dimensions of brick walls.

Automatic throttles are placed in the openings of the outer wall for internal circulation control. The automatic opening of the throttles was achieved by reaching the air in the vicinity of the absorber at a temperature higher than the air temperature in the internal gap. Closure of the throttle limiting reversible air movement and counteracting the cooling of the interior of the wall at night time or in case of insufficient sunlight.

4. Results and discussions

In order to determine the efficiency of the tested variants of the wall, the components of the monthly balance were determined: heat loss due to air permeability on both sides (Table 1) and heat gains from absorbed sunlight (Table 2).

One of the criteria for assessing energy efficiency is the comparison of profit and loss over the period considered. In Figure 5, the SPKA heat balance values calculated as the difference between heat gains Q_s and heat losses Q_h in monthly intervals. The greatest gains occur in transitional periods, regardless of the SPKA material configuration considered. At this time, the wall in the monthly interval does not generate losses. The energy benefits obtained can be used to reduce the overall heat demand of the entire building. In the middle months of the high heating season (November till February) the profit level is much lower, and in the case of a wall made of ordinary concrete, heat

losses are slightly outweighed. By referring to the results of monthly solar radiation reaching the surface of the glazing, one may determine the efficiency of the individual material configurations of the solution being tested.

Table 1. Summary of calculated monthly heat losses by 1 m²; SPKA concrete (C), autoclaved aerated concrete (AAC), Calcium Silicate bricks (CS)

month	Heat losses Q _h by 1 m ² SPKA [Wh]					
	Wall with a single-glazed glass U _g =0.6 [W/m ² K]			Wall with a double-glazed glass U _g =1.2 [W/m ² K]		
	C	AAC	CS	C	AAC	CS
X	7293.9	2917.6	5737.9	7974.7	3014.8	6186.1
XI	9706.2	3882.5	7635.5	10612.1	4011.9	8153.2
XII	11845.2	4738.1	9318.2	12950.8	4896.0	9950.0
I	13708.5	5483.4	10784.0	14988.0	5666.2	11515.1
II	9913.9	3965.6	7799.0	10839.3	4097.8	8327.7
III	10629.0	4251.6	8361.5	11621.0	4393.3	8928.4
IV	6477.8	2591.1	5095.9	7082.4	2677.5	5441.4
Total [Wh]	69574.5	27829.9	54732	76068.3	28757.5	58501.9

Table 2. Summary of calculated monthly heat gains by 1m² SPKA

month	Heat gains Q _s by 1 m ² SPKA [Wh]					
	Wall with a single-glazed glass U _g =0.6 [W/m ² K]			Wall with a double-glazed glass U _g =1.2 [W/m ² K]		
	C	AAC	CS	C	AAC	CS
X	19658.0	11646.5	19322.68	17912.5	10643.2	17214.4
XI	12592.0	7638.6	12367.54	11678.5	6968.4	11303.2
XII	10996.1	6765.5	10844.99	10237.9	6153.5	9968.7
I	12496.3	7960.2	12266.93	11808.0	7249.6	11742.1
II	15613.1	9596.4	15307.19	14653.1	8751.3	14329.8
III	22411.1	13583.9	21955.79	20849.4	12406.6	20391.8
IV	30653.7	17969.6	30152.9	27696.0	16431.5	26508.6

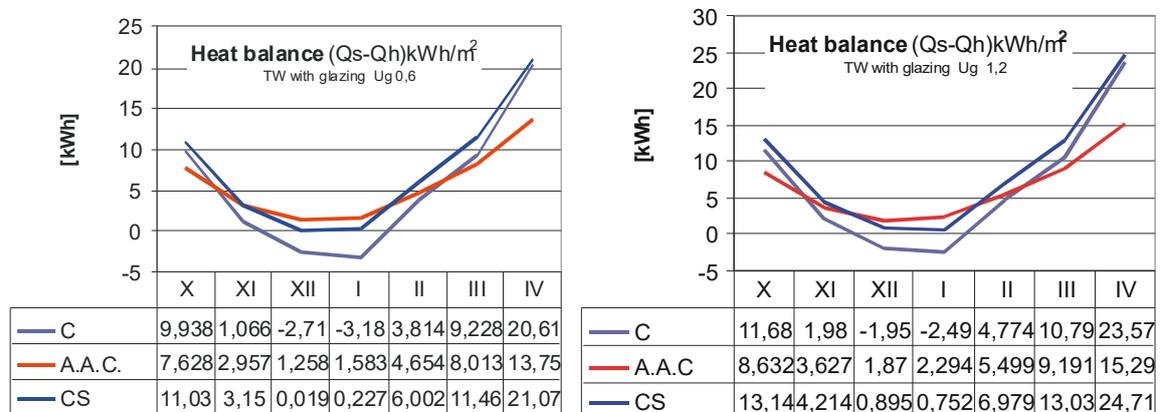


Figure 5. Heat balance values calculated as a difference between heat gains Q_s and heat losses Q_h in monthly intervals

On a monthly average and whole heating season, SPKA's solar energy efficiency was between 25% and less than 28% in the case of a wall with a plain or silicon base concrete, depending on the glazing used, and between 15% and 17.5% for the wall made of AAC concrete. However, in the months with the lowest sun exposure, i.e. in December and January, the most advantageous ratio of heat gains to heat losses was found in the solution using AAC concrete.

5. Conclusions

In the presented solution of the modified Trombe wall, with the use of air circulation for the internal distribution of the absorbed heat it has demonstrated the possibility of using autoclaved aerated concrete. Although the efficiency of the use of solar radiation was lower in this kind of solution during the whole heating season, however, the heat balance of the wall was only marginally lower in comparison to the solutions based on materials with higher density. In the months with the lowest amount of solar radiation, the wall containing the autoclaved aerated concrete had better thermal balance, that, taking into consideration irregularity of the solar radiation in Eastern part of Europe, makes it a safe solution. Presumably, an additional improvement in the efficiency of heat distribution in an autoclaved aerated concrete based wall would be possible by replacing the inner masonry by ordinary concrete, silicate bricks or PCM based composite. The analysis of these options is planned as a continuation of future research.

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